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Research Article

Bilingualism and Procedural Learning in Typically Developing Children and Children With Language Impairment

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Purpose: The aim of this study was to investigate whether dual language experience affects procedural learning ability in typically developing children and in children with specific language impairment (SLI).
Method: We examined procedural learning in monolingual and bilingual school-aged children (ages 8–12 years) with and without SLI. The typically developing children (35 monolinguals, 24 bilinguals) and the children with SLI (17 monolinguals, 10 bilinguals) completed a serial reaction time task.
Results: The typically developing monolinguals and bilinguals exhibited equivalent sequential learning effects, but neither group with SLI exhibited learning of sequential patterns on the serial reaction time task.
Conclusion: Procedural learning does not appear to be modified by language experience, supporting the notion that it is a child-intrinsic language learning mechanism that is minimally malleable to experience.

People with specific language impairment (SLI), or primary language impairment as it is also known, have language difficulties in the absence of a known cause, such as intellectual disabilities, frank neurological disorders, or emotional or social dysfunctions (Leonard, 2014). Although the cause or causes of SLI are unknown, heritability estimates suggest genetic contributions (e.g., Tomblin & Buckwalter, 1998). While some candidate genes have been identified (e.g., Rice, Smith, & Gayan, 2009), the progress has been erratic, perhaps because diagnostic categories like SLI are likely to be heterogeneous with different genetic and environmental underlying causes contributing to the heterogeneity (Bishop, 2006). Therefore, an adequate understanding of SLI requires not only investigation of language learning mechanisms that are intrinsic to the child but also investigation of how environmental or extrinsic factors shape development. Bilingual language learning environments provide us with an opportunity to examine how child-extrinsic factors shape language development.

Thus far, research on describing SLI in bilingual children has been considered challenging for a number of reasons. First, tests are unavailable in many of the languages spoken by children from diverse home language backgrounds. Second, even when tests are available, they are often not standardized or are not sufficiently valid, as the norms are typically developed based on performance by children who are monolingual (Kohnert, 2010). Third, bilingual children may score lower than monolinguals by virtue of the reduced exposure to either language relative to monolingual children (Gollan, Montoya, Cera, & Sandova, 2008). Fourth, language dominance of bilingual children may vary depending on the context of language use (e.g., home vs. school) and the topics of discussion (e.g., describing a family celebration vs. a scientific experiment). Fifth, the rate of development in different linguistic subdomains (e.g., semantics vs. syntax) may differ as a function of the languages spoken and the types of language assessment employed (e.g., morphosyntactic vs. narrative tasks; Kohnert, 2010). Sixth and finally, linguistic knowledge in one language

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may influence a child's performance in the other language. For example, typically developing (TD) bilingual children produce syntactic errors that may resemble those produced by monolingual children with SLI as a consequence of constructions used in their other language (e.g., Paradis, 2005; Restrepo & Gutierrez-Clellen, 2001).

Extrinsic factors, such as dual language experience, combine with factors intrinsic to the child to generate an individual language-cognitive profile. The intrinsic factors may include not only linguistic abilities but also nonlinguistic cognitive abilities. Given the difficulties of language assessment in bilingual children, a complete characterization of SLI requires investigation of nonlinguistic and linguistic abilities vis-à-vis language experience. Procedural learning is a nonlinguistic ability that should be considered because procedural learning has been posited to be crucial for language learning (e.g., Hsu & Bishop, 2010; Ullman, 2004; Ullman & Pierpont, 2005). Accordingly, in this study, we examined procedural learning in monolingual and bilingual children with and without SLI.

Procedural Learning

Procedural learning refers to the learning of sequential skills (Ullman & Pierpont, 2005). Such learning depends on the procedural memory system, which is supported by the frontal–basal ganglia circuits (Ullman, 2001, 2004; Ullman & Pierpont, 2005). The procedural memory system is part of the implicit memory system that is involved in sequentially structured motor and cognitive learning (cf., Rosenbaum, 2010, 2017) and is hypothesized to be independent of the declarative memory system responsible for propositional fact learning (Ullman, 2001, 2004). Procedural learning is evident when individuals' performance becomes rapid after an adequate amount of exposure to sequences whose underlying structure needs to be inferred (Ullman & Pierpont, 2005).

Procedural learning is often measured with the serial reaction time (SRT) task (Cherry & Stadler, 1995; Nissen & Bullemer, 1987; Thomas & Nelson, 2001; Vakil, Kahan, Huberman, & Osimani, 2000). Here, in its typical instantiation, participants are asked to view a visual stimulus appearing in one of four horizontally arranged boxes on a computer screen. As each stimulus appears, the participant is supposed to press a corresponding button as quickly and accurately as possible (e.g., Tomblin, Mainela-Arnold, & Zhang, 2007). Procedural learning is typically indexed by a reduction of response times for repeated sequences as opposed to random sequences (Karuza et al., 2013; Nissen & Bullemer, 1987; Willingham, Nissen, & Bullemer, 1989).

Procedural Learning and Language Abilities in Monolinguals

The assessment of procedural learning using the SRT task is relevant to language assessment because the procedural memory system has been proposed to be more affected in individuals with SLI than the declarative memory system (i.e., the procedural deficit hypothesis; Ullman & Pierpont, 2005). Empirically, monolinguals with SLI have a slower learning rate (i.e., the SLI group needs more trials to learn sequences compared to TD peers) or lack of learning altogether on procedural learning tasks relative to their TD peers (Adi-Japha, Strulovich-Schwartz, & Julius, 2011; Kemény & Lukács, 2010; Lum, Conti-Ramsden, Morgan, & Ullman, 2014; Lum, Conti-Ramsden, Page, & Ullman, 2012; Lum, Gelgec, & Conti-Ramsden, 2010; Sanjeevan et al., 2015; Tomblin et al., 2007). In regard to linguistic domains, the procedural deficit hypothesis predicts that grammar learning depends on the procedural memory system, whereas vocabulary learning relies on the declarative memory system (Ullman & Pierpont, 2005). This hypothesis is well aligned with the findings that children with SLI tend to exhibit more prominent problems in grammar than in other linguistic domains (Leonard, 2014). Further evidence consistent with this hypothesis comes from Tomblin et al. (2007), who found that adolescents with SLI showed slower procedural learning rates on the SRT task than adolescents without SLI. Moreover, their performance on the SRT task was associated with lower grammar scores but was not related to their vocabulary scores. Taken together, the procedural deficit hypothesis and empirical findings related to the hypothesis suggest that poor procedural learning is an intrinsic characteristic of many children with SLI.

Bilingual Influence on Procedural Learning

As mentioned above, poor procedural learning appears to be an intrinsic characteristic of many individuals with SLI, but bilingual children with SLI may be an exception. Bilingual children regularly exercise procedural learning to navigate two languages, which possibly enhances their procedural learning capacity relative to monolinguals (MacWhinney, 2002). If so, bilingual experience might offset the effects of language impairment, yielding better procedural learning in bilingual children with SLI as opposed to monolingual children with SLI.

Only a handful of studies have examined TD bilingual children's procedural learning, and those studies have often employed a statistical learning task. *Statistical learning* refers to the ability to track distributional information in sensory input, and this process is thought to significantly overlap with procedural learning (e.g., Perruchet & Pacton, 2006), particularly in tasks that involve acquisition of sequences (Hsu & Bishop, 2010). To date, the results of sequence learning tasks with bilinguals have been mixed. Yim and Rudoy (2012) tested monolingual and bilingual children between the ages of 5 and 13 years who acquired their second language (L2) after age 3 years on both a nonlinguistic auditory tones task and a visual statistical learning task. Learning was equivalent across both groups, suggesting that sequential statistical learning abilities may not be influenced by multilanguage proficiency. However, more recent work has reported a difference in a dual-language statistical learning task in infants at 14 months of age, in which bilinguals, but not monolinguals, were able to acquire two artificial languages presented sequentially using only transitional probability cues (Antovich & Graf Estes, 2017). The discrepant statistical learning findings in infancy are mirrored in adult studies as well. Dual-language statistical learning studies have found no differences in performance between monolingual and bilingual adults (Bogulski, 2013; Bulgarelli & Weiss, 2016). However, studies of sequential statistical learning that involve the suppression of competing cues did find differences between monolingual and bilingual adults (Bartolotti, Marian, Schroeder, & Shook, 2011; Wang & Saffran, 2014). Moreover, in a nonsequential cross-situational statistical learning task in which learners mapped words to objects, Poepsel and Weiss (2016) found that bilinguals (all late L2 learners) outperformed monolinguals in mapping multiple objects to a single word but performed equivalently in the context of one-to-one mappings. Consequently, Poepsel and Weiss (2016) argued that bilingual learning differences in adult statistical learning may extend only to tasks that involve integrating information over time (Erickson & Thiessen, 2015). The above results may indicate that sequence learning tasks, which neither involve the suppression of competing cues nor involve integrating information over time, are unlikely to elicit differences between monolinguals and bilinguals.

It should be noted, however, that there is also some evidence that continuous measures of learning (e.g., reaction times [RTs]) might provide greater sensitivity for detecting differences in tracking regularities between monolinguals and bilinguals. Bonifacci, Giombini, Bellochi, and Contento (2011) found that bilingual children (between 6 and 12 years old) and bilingual adolescents to young adults (between 14 and 22 years of age) produced shorter RTs in anticipating upcoming elements in a sequence-learning task relative to their monolingual peers, despite the overall accuracies being similar between the bilinguals and monolinguals at each age group.

Inspired by the possibility that continuous learning measures could provide greater sensitivity for detecting differences in procedural learning, we compared monolingual and bilingual children using an SRT task. We asked whether an extrinsic factor, dual language experience, is associated with differences in procedural learning. More specifically, we asked if there is a significant difference in procedural learning between TD monolingual and bilingual children and between monolingual and bilingual children with SLI. We also examined whether language experience, as indicated by age of acquisition of English and time spent hearing and speaking the home language, was correlated with procedural learning in bilingual children. If the core procedural learning abilities are unaffected by prior language experience (Poepsel & Weiss, 2016), then there should be no differences in RT between TD bilingual and monolingual children and between bilingual and monolingual children with SLI. However, if a bilingual advantage is manifested in enhanced procedural learning, as suggested by the anticipation study of Bonnifacci et al. (2011), then one would expect bilinguals, both TD and those with SLI, to exhibit more pronounced RT differences between the pattern phase and the random phase relative to monolinguals. In addition, we examined the role of the child-intrinsic factor of language impairment by comparing procedural learning in children with SLI to TD peers.

Method

Participants

Eighty-six children participated in this experiment: 35 monolingual typically developing (MO-TD), 24 bilingual typically developing (BI-TD), 17 monolingual SLI (MO-SLI), and 10 bilingual SLI (BI-SLI), all aged 8–12 years. Because our primary focus was comparing monolingual children to bilingual children, we conducted an a priori power analysis to ensure that we had sufficient power to detect these differences. An analysis using the G*Power program (Faul, Erdfelder, Lang, & Buchner, 2007) indicated that a total sample of 52 participants would be needed to detect small effects ($d = 0.2$) with 80% power using the repeated-measures analysis of variance (ANOVA) for the critical Phase (Random vs. Pattern) × Group interaction with alpha at .05. For comparisons of TD participants, the sample size was adequate. For comparisons of SLI participants, it was not; therefore, nonparametric statistics were used.

All children met the following inclusion criteria: (a) nonverbal IQ above 75 as measured by the Wechsler Abbreviated Scale of Intelligence–Second Edition (Wechsler, 2011) and (b) normal hearing based upon a hearing screening. Based on information collected via parental phone screening, a written background health questionnaire, and observation during the testing sessions, children were excluded from participating if they met any of the following criteria: (a) intellectual disability; (b) emotional or behavioral disturbances, including autism; (c) frank signs of neurological disorder; or (d) seizure disorders or use of medication to control seizures.

The nonverbal IQ cutoff of 75 was chosen to rule out intellectual disability. Children with SLI whose nonverbal IQ scores are below the more traditional cutoff score of 85 but above 70 do not differ from children with SLI in their response to intervention (e.g., Cole, Coggins, & Vanderstoep, 1999; Fey, Long, & Cleave, 1994) or in their language and cognitive profiles (Leonard, 2007; Tomblin & Nippold, 2014; Tomblin & Zhang, 1999). Furthermore, matching children on nonverbal IQ, or using IQ as a covariate, leads to unrepresentative samples of children and uninterpretable data (Dennis et al., 2009; Earle, Gallinant, Grela, Lehto, & Spaulding, 2017).

All monolingual children used English at home and at school. They had minimal exposure to other languages (less than 5% hearing or speaking other languages in addition to English, except for two children who had 15% exposure to other languages) by parental report. In order to ensure a significant degree of bilingualism in the bilingual children, children in the BI-TD and BI-SLI groups were required (per parental questionnaire): (a) to have at least

3 years of English exposure;[1] (b) use their home language with at least one member of the household and attend school and community events in English to ensure continued use of both their home language and English;[2] and (c) use their home language at least 20% of the time (Hoff et al., 2012; Place & Hoff, 2011). The requirement (a) was used to make sure that the bilingual children had an adequate exposure to English and could be assessed in the English language measures. The requirements (b) and (c) were used to make sure that children were continuously exposed to both languages on a regular basis.

MO-TD children were native English speakers who had been minimally exposed to other languages on a regular basis, whereas the BI-TD group had various other language backgrounds (10 Korean, 9 Chinese, 2 German, 1 Bengali, 1 French, and 1 Spanish) in addition to English. MO-SLI children were native English speakers and had been minimally exposed to other languages, whereas the BI-SLI children had various other language backgrounds (1 Albanian, 2 Bengali, 1 Chinese, 1 Farsi/Dari, 3 Korean, 1 Ojibwe, and 1 Spanish). TD children were recruited in Toronto, Ontario, Canada, and in the community around State College, Pennsylvania, using flyers in community locations and invitation letters distributed in schools. Children with SLI were recruited only in Toronto.

Standardized Tests and Language History in the Parental Questionnaire

A battery of standardized language tests was administered to all children. The Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003) was used to test children's English language abilities, and a language background questionnaire was used to assess children's language history and experience. For the MO-TD group, the criterion for inclusion was higher than standard scores of 81 (1.25 *SD*s below the mean) on the Receptive Language Index (RLI), Expressive Language Index (ELI), and Core Language Score (CLS) on the CELF-4.

For the BI-TD group, parental report was used to ensure typical development. CELF-4 norms are based on a monolingual norming sample, and they do not provide appropriate standards for defining language status in bilinguals (Bedore & Peña, 2008; Kohnert, 2010). However, all the BI-TD children attained language scores higher than 81 on the RLI, ELI, and CLSs on the CELF-4. Out of 24 in the BI-TD group, 21 children were English dominant, two children were equally proficient in both languages, and one child was dominant in the home language per parental report. See Table 1 for children's demographic information and performance on the standardized tests. The group comparisons indicate that there were no significant differences in age, socioeconomic status (SES; i.e., primary caregivers' years of education), nonverbal IQ, and overall language abilities between the BI-TD and MO-TD groups. As Table 1 shows, children in the MO-TD group in Toronto had slightly lower SES, $t(33) = 2.45$, $p = .020$, and lower CLS, $t(33) = 2.06$, $p = .047$, relative to the MO-TD group in Pennsylvania. However, with the two locations combined, the MO-TD and BI-TD groups showed comparable performance (nonverbal IQ, overall language abilities) and demographic profiles (age, SES).

For the primary inclusionary criteria of SLI, we relied on two sources from the child's immediate environment. Children with SLI were required to be identified as having language learning difficulties by the Toronto District School Board,[3] and on the parental report, children's parents were required to express concern about the children's language development, including speaking, understanding, reading, or writing. In addition, we ensured that all the children with SLI were English dominant per parental report and received standard scores at or below 81 (1.25 *SD*s below the mean) on one or more of the RLI, ELI, and CLSs on the CELF-4. Table 2 shows the SLI group's demographic information and performance on the standardized tests. The MO-SLI group and BI-SLI group comparisons indicated that there were no significant differences in age, SES, and overall English language abilities, but there was a significant difference in nonverbal IQ ($p = .040$).

SRT Task

Stimuli

The SRT task was adapted from the task used by Tomblin et al. (2007). The stimuli consisted of images of four boxes arranged horizontally on a screen. An initial image with all empty boxes appeared for 500 ms, and then, an appealing, child-friendly creature appeared in one of the four boxes. Once the child pressed a button corresponding to the location of the creature, another empty set of boxes appeared. This process continued for four phases, consisting of 100 trials each. A short break of less than 3 min was presented between each phase to alleviate fatigue. The four phases included Random Phase 1, Pattern Phase 1, Pattern Phase 2, and Random Phase 2. Random Phase 1 was presented to establish baseline performance. The Pattern Phase 1 and Pattern Phase 2 included a sequence of an image appearing in four locations in a fixed order (1-3-2-4-4-2-3-4-2-4) presented 10 times. Consistent with previous studies (Lum et al., 2012; Tomblin et al.,

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[1] One participant with SLI had 2.5 years of English exposure.

[2] One TD participant in Toronto had English as home language and French as school language, and one SLI participant had English as home language and Ojibwe as school language.

[3] Two bilingual children were not referred by the Toronto District School Board. However, we included these children in the SLI group because their parents expressed concerns about their language abilities, and they were receiving language services or advised to receive language services at their schools.

Table 1. TD group's demographic information and performance on the standardized tests.

	Monolinguals						Bilinguals						Monolinguals vs. bilinguals
	Total (35)		Pennsylvania (15)		Ontario (20)		Total (24)		Pennsylvania (7)		Ontario (17)		*t* (independent-samples *t* tests)
Variable	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	
Age	10.45	1.43	10.32	1.63	10.55	1.29	10.00	1.45	10.40	1.50	9.83	1.44	1.19
[a]SES	17.49	2.65	18.67	2.69	16.60	2.30	17.67	3.05	18.86	2.27	17.18	3.24	0.24
[b]IQ	110.94	13.96	115.73	13.55	107.35	13.48	115.38	13.81	114.57	13.08	115.71	14.47	1.20
[c]CLS	111.37	12.90	116.33	10.57	107.65	13.48	110.67	12.23	111.86	10.11	110.18	13.26	0.21
[d]RLI	111.89	13.67	117.27	10.51	107.85	14.59	113.92	12.18	113.57	12.58	114.06	12.40	0.59
[e]ELI	112.71	14.95	118.67	13.40	108.25	14.79	111.12	13.21	111.29	7.93	111.06	15.07	0.42
[f]Age of acquisition (English)							3.50	2.25	5.00	1.73	2.88	2.18	
[g]Daily exposure (hearing)							64.88	20.71	62.86	17.99	65.71	22.20	
[g]Daily exposure (speaking)							51.88	29.07	51.43	25.45	52.06	31.18	

Note. TD = typically developing; SES = socioeconomic status; CLS = Core Language Score; RLI = Receptive Language Index; ELI = Expressive Language Index.

[a]SES quantified as maternal years of education. [b]Nonverbal Intelligence Quotient: The Perceptual Reasoning Index of the Wechsler Abbreviated Scale of Intelligence–Second Edition (Wechsler, 2011). [c]Core Language Score on English Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel et al., 2003). [d]Receptive Language Index on English CELF-4. [e]Expressive Language Index on English CELF-4. [f]Age of acquisition: parental report of when child began hearing English. [g]Daily exposure: parental estimate of % time the child is exposed to home language during typical weekdays at home.

2007), we expected that, if children learned the sequences during the pattern phases, children's RTs would slow down in the second random phase due to the unanticipated introduction of random order after fixed order. Thus, the inclusion of both random and pattern phases allowed us to compare learning that is specific to the patterned structure of the stimuli: Learning was indexed by faster response times in the pattern phase as opposed to slower response times in the random phase. The greater the difference between the pattern and random phases, the better the child's procedural learning.

Procedure

E-Prime software 2.0, standard (Schneider, Eschman, & Zuccolotto, 2012) and an E-Prime response box were used to present the stimuli and record response time and accuracy. The children were asked to place their index and middle fingers from both hands on the four horizontally arranged buttons on the response box, each of which corresponded to one of the four boxes on the screen. They were asked to press a button as quickly as possible to catch a creature that would appear in one of the four boxes. Before the test trials, a series of practice trials with feedback was

Table 2. SLI group's demographic information and performance on the standardized tests.

	Monolinguals (17)	Bilinguals (10)	Monolinguals vs. bilinguals
Variable	*Mdn*	*Mdn*	*z* (Mann–Whitney *U* test)
Age	9.67	9.21	–0.78
[a]SES	14.00	14.00	–1.84
[b]IQ	85.00	101.00	–2.04*
[c]CLS	76.00	75.00	–0.60
[d]RLI	79.00	81.50	–1.36
[e]ELI	77.00	73.00	–1.13
[f]Age of acquisition (English)		2.25	
[g]Daily exposure (hearing)		40.00	
[g]Daily exposure (speaking)		20.00	

Note. Independent-samples Mann–Whitney *U* tests were used for monolingual and bilingual comparisons in the SLI group due to nonnormal distribution. SLI = specific language impairment; SES = socioeconomic status; CLS = Core Language Score; RLI = Receptive Language Index; ELI = Expressive Language Index.

[a]SES quantified as maternal years of education. [b]Nonverbal intelligence quotient: the Perceptual Reasoning Index of the Wechsler Abbreviated Scale of Intelligence–Second Edition (Wechsler, 2011). [c]Core Language Score on English Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel et al., 2003). [d]Receptive Language Index on English CELF-4. [e]Expressive Language Index on English CELF-4. [f]Age of acquisition: parental report of when child began hearing English. [g]Daily exposure: parental estimate of % time the child is exposed to home language during typical weekdays at home.

*$p < .05$.

provided to all children in order to teach them to map the location of the creature's appearance on the screen to a corresponding button. During the test trials, in each phase, the children continued to press the appropriate button in response to each appearance of the stimulus. After each phase, a short break of less than 3 min was given to the children.

Statistical Analyses

Analyses included the children's accuracy and RT performance. Only correct responses were included for RT analysis. Prior to the parametric analysis, outliers were removed from further analysis when any values of the accuracy and RT were greater than an absolute value of 3.29 (Tabachnick & Fidell, 2013). For the nonparametric analyses, all the outliers were included. We considered that the data were normally distributed when the values were less than an absolute value of 2 for skewness and kurtosis (George & Mallery, 2010). Only the MO-SLI group had a nonnormal distribution by these criteria. To measure procedural learning, consistent with previous studies (Lum et al., 2010, 2012; Siegert, Taylor, Weatherall, & Abernethy, 2006), we compared the children's performance in the second pattern phase (100 trials) with the second random phase (100 trials). Because children in the SLI groups had slower RT across several blocks, we controlled within-subject variability in motor speed by converting each child's RTs to *z*-scores referenced to the mean and standard deviation across all correct trials for each individual child (Thomas et al., 2004). Then, the *z*-scored RT values were used for further analysis. The MO-TD group was compared with the BI-TD group using two repeated-measures ANOVAs with group (MO-TD, BI-TD) as a between-subjects factor and phase (Pattern 2, Random 2) as a within-subject factor. The dependent variables in the two analyses were accuracy and RT. For the comparisons that included SLI groups, nonparametric tests were conducted due to the small sample size and nonnormal distribution. Specifically, the Mann–Whitney *U* test, the equivalent of the independent *t* test, was conducted to examine group differences in procedural learning by comparing difference scores between phases (e.g., pattern and random phases) between groups. The Wilcoxon signed-ranks test, the equivalent of the paired *t* test, was also conducted to examine any evidence of pattern learning by comparing differences between phases (e.g., pattern and random phases) within each group.

Because the data were collected in Ontario and Pennsylvania for the TD groups, we determined whether we could combine the accuracy and RT data across the two different locations. The test results confirmed that it was appropriate to combine data across the locations (see Appendix for a report of the statistical analyses).

Although the MO-SLI and BI-SLI groups differed in IQ, it was not used as a covariate in further analysis because, overall, the correlation between the nonverbal IQ scores and our procedural learning measure was not significant for accuracy ($r = -.15$, $p = .189$) nor RTs ($r = .09$, $p = .416$). The nonsignificant results confirmed that there was no need to include IQ as a covariate.

Results

We first asked whether language experience shapes procedural learning differently in monolingual and bilingual children with typical development by examining learning of the SRT sequence in these groups. The group mean values of SRT performance are shown in Table 3 for the repeated-measures ANOVA for the TD groups.

The repeated-measures ANOVA, with accuracy as the dependent variable, indicated that none of the effects were significant: the main effect of phase, $F(1, 56) = 0.53$, $p = .470$, $\eta_p^2 = .009$, the main effect of group, $F(1, 56) = 0.47$, $p = .494$, $\eta_p^2 = .008$, and the Phase × Group interaction, $F(1, 56) = 0.64$, $p = .427$, $\eta_p^2 = .011$.

The repeated-measures ANOVA, with RT as the dependent variable, indicated that there was a significant main effect of phase, $F(1, 56) = 5.57$, $p = .022$, $\eta_p^2 = .090$. However, neither the main effect of group, $F(1, 56) = 0.37$, $p = .544$, $\eta_p^2 = .007$, nor the Phase × Group interaction were significant, $F(1, 56) = 0.08$, $p = .785$, $\eta_p^2 = .001$. As can be seen in Figure 1, all TD children showed a slower RT performance in the random phase compared with the pattern phase. However, this pattern did not significantly differ between the two groups, which indicated that both monolinguals and bilinguals exhibited a comparable learning effect.

We then asked whether language experience modulates procedural learning differently in monolingual and bilingual children with language impairment by examining learning of the SRT sequence in bilingual and monolingual children with SLI. The median values of SRT performance are shown in Table 4 for the Mann–Whitney *U* test for the SLI group comparisons.

The difference scores between the second pattern and second random phases in accuracy were not statistically significantly different between MO-SLI ($Mdn = 0.00$) and BI-SLI ($Mdn = 1.00$), $U = 75.50$, $z = -0.48$, $p = .639$, $r = -.09$. Also, the difference scores in RT were not statistically significantly different between MO-SLI ($Mdn = -0.03$) and BI-SLI ($Mdn = -0.01$), $U = 76.00$, $z = -0.45$, $p = .675$, $r = -.09$. As depicted in Figure 2, MO-SLI and BI-SLI showed comparable RT differences between the pattern phase and the random phase.

We then examined whether the MO-SLI and BI-SLI groups showed any evidence of pattern learning by comparing differences between the pattern and random phases. No difference between the random and pattern phases were found in either MO-SLI, $z = -0.19$, $p = .850$, $r = .05$, or BI-SLI, $z = -0.15$, $p = .878$, $r = .05$. Taken together, neither the MO-SLI group nor the BI-SLI group showed significant pattern learning, and the two groups did not differ with regard to the pattern versus random phase difference.

Because the learning rate may be different across the pattern phases between the MO-SLI and BI-SLI

Table 3. Accuracy and *z*-score RT performance on the SRT task in TD groups.

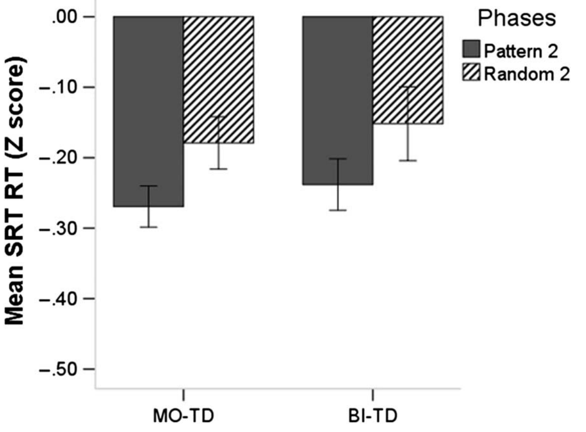
	Monolinguals						Bilinguals					
	Total (35)		Pennsylvania (15)		Ontario (20)		Total (24)		Pennsylvania (7)		Ontario (17)	
Performance	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***	***M***	***SD***
Pattern accuracy	93.11	5.26	92.67	5.02	93.45	5.53	93.83	3.87	94.86	4.14	93.41	3.81
Random accuracy	92.11	5.91	91.60	5.80	92.50	6.12	93.88	3.84	93.29	3.59	94.12	4.01
z-score pattern RT	−0.27	0.17	−0.29	0.14	−0.25	0.20	−0.24	0.18	−0.33	0.16	−0.20	0.18
z-score pattern RT	−0.18	0.22	−0.17	0.20	−0.19	0.24	−0.15	0.26	−0.17	0.16	−0.14	0.29

Note. RT = reaction time; SRT = serial reaction time; TD = typically developing.

groups, we examined performance between the two SLI groups across the pattern trials by comparing RT difference between the first and second pattern phases. The Mann–Whitney *U* tests revealed that the RT difference scores between the first pattern phase and the second pattern phase did not significantly differ between the MO-SLI group (*Mdn* = −0.06) and the BI-SLI group (*Mdn* = −0.18), *U* = 48.00, *z* = −1.86, *p* = .066, *r* = −.36. Within each MO-SLI and BI-SLI group, the Wilcoxon signed-ranks tests revealed that RT in Pattern 2 (*Mdn* = −0.29) did not significantly differ from RT in Pattern 1 (*Mdn* = −0.22) in MO-SLI, *z* = −1.44, *p* = .149, *r* = −.35, whereas RT in Pattern 2 (*Mdn* = −0.29) was significantly faster than RT in Pattern 1 (*Mdn* = −0.14) in BI-SLI, *z* = −2.60, *p* = .009, *r* = −.82. The results indicate that children in the BI-SLI group showed a significant RT reduction between Pattern 1 and Pattern 2, whereas children in the MO-SLI group did not. However, this pattern difference was not significant when the two groups were directly compared in the Mann–Whitney *U* tests.

To further examine the relationship between language experience and procedural learning, we examined correlations between estimates of bilingual experience and SRT performance in all bilingual children (combining 24 BI-TD and 10 BI-SLI children: *n* = 34) using Pearson correlation coefficients. More specifically, we examined whether three measures of language experience—age of acquisition of English, percentage of time hearing the home language, and percentage of time speaking the home language—were correlated with SRT RT difference scores between the second pattern and the second random phase in bilingual children. Because all of the bilingual children attended English-speaking elementary schools, the percentage of time hearing or speaking the home language indicates the bilinguals' relative balance of exposure and use of both languages. The results revealed that there were no significant correlations of SRT RT difference scores with age of acquisition of English (*r* = .27, *p* = .124), with percentage of time hearing the home language (*r* = .04, *p* = .832), and with percentage of time speaking the home language (*r* = .01, *p* = .969). Additional correlation analyses within the BI-TD children (*N* = 24) using the Pearson correlation coefficients confirmed that there were no significant correlations between bilingual exposure and SRT performance: SRT RT difference scores with age of acquisition of English (*r* = .17, *p* = .417), with percentage of time hearing the home language (*r* = −.25, *p* = .239), and with percentage of time speaking the home language (*r* = −.17, *p* = .437). Correlations within the BI-SLI group only were not examined due to the small sample size (*n* = 10).

Figure 1. Serial reaction time (SRT) performance in typically developing groups across two phases. Positive values indicate slower RT. Error bars represent ±1 *SE* of the means. RT = reaction time; MO-TD = monolingual typically developing; BI-TD = bilingual typically developing.



Finally, we sought to confirm that our data replicate the reported differences in procedural learning in children with SLI and TD. To address this issue, we directly compared TD and SLI groups in each monolingual and bilingual population to determine whether there were differences in procedural learning. The Mann–Whitney *U* test was conducted to determine whether there were differences in difference scores between the phases between TD and SLI groups.

For the monolingual children, the difference scores in accuracy were nonsignificant between MO-TD (*Mdn* = −1.00) and MO-SLI (*Mdn* = 0.00), *U* = 277, *z* = −0.40, *p* = .688, *r* = −.06. Also, the difference scores in RT were nonsignificant between MO-TD (*Mdn* = 0.04) and MO-SLI (*Mdn* = −0.03), *U* = 248, *z* = −0.97, *p* = .334, *r* = −.13. For the bilingual children, the difference scores in accuracy

Table 4. Accuracy and *z*-score RT performance on the SRT task in SLI groups.

	Monolinguals	**Bilinguals**	
	Total (17)	**Total (10)**	**Monolinguals vs. bilinguals**
Performance	***Mdn***	***Mdn***	***z* (Mann–Whitney *U* test)**
Pattern accuracy	89.00	93.00	−0.25
Random accuracy	90.00	91.50	−0.25
z-score pattern RT	−0.29	−0.29	−0.30
z-score random RT	−0.27	−0.34	−0.15

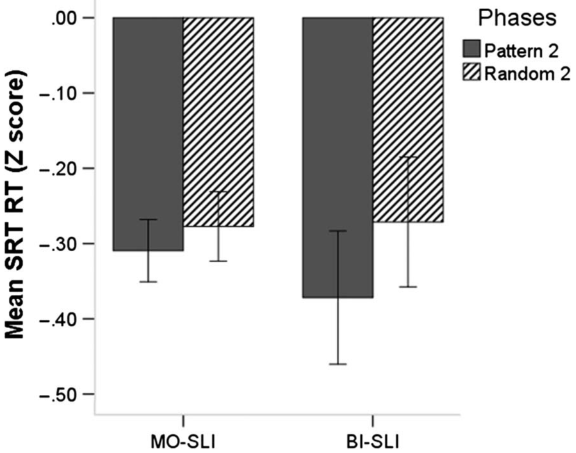
Note. Mean values were presented to be comparable to Table 3 for the TD groups, but mean rank values were also presented in the table for Mann–Whitney *U* tests. RT = reaction time; SRT = serial reaction time; SLI = specific language impairment; TD = typically developing.

were nonsignificant between BI-TD (*Mdn* = −0.50) and BI-SLI (*Mdn* = 1.00), *U* = 98, *z* = −0.84, *p* = .404, *r* = −.12. Also, the difference scores in RT were nonsignificant between BI-TD (*Mdn* = 0.07) and BI-SLI (*Mdn* = −0.01), *U* = 114, *z* = −0.23, *p* = .821, *r* = −.03.

Discussion

We asked whether language experience shapes procedural learning differently in monolingual and bilingual children with and without SLI. We hypothesized that if a bilingual advantage is manifested in enhanced procedural learning, both TD bilinguals and bilinguals with SLI would exhibit more pronounced RT differences between the pattern phase and the random phase relative to monolinguals as suggested by Bonifacci et al., 2011. However, if the core procedural learning abilities are unaffected by prior language experience (Poepsel & Weiss, 2016), then there should be no differences in RT between the monolingual and bilingual groups with/without SLI. Our results lend support to the latter hypothesis in both typical and disordered development as RTs did not differ between monolinguals and bilinguals regardless of language status. Thus, our results suggest that the experience of acquiring two languages does not influence this proposed core language learning mechanism. Both TD groups, monolingual and bilingual, exhibited procedural learning effects as evidenced by faster RTs for patterned stimuli relative to random ones. However, the SLI groups did not exhibit RT differences between patterned and random sequences, indicating that they were unable to acquire, insofar as we could tell, the patterns within the context of our experimental procedure. Notably, the BI-SLI group showed a faster RT in Pattern 2 than in Pattern 1, indicating a different learning pattern than that observed in the MO-SLI group. However, the direct group comparison between the MO-SLI and BI-SLI groups suggested that there was no group difference for the patterned sequence phases. Additionally, we examined the correlations between bilingual experience and SRT within bilingual children. We did not find any significant correlations between these factors and SRT performance. These results support the hypothesis that this type of procedural learning is not modified by language experience.

Figure 2. Serial reaction time (SRT) performance in SLI groups across two phases. Positive values indicate slower RT. Error bars represent ±1 *SE* of the means. SLI = specific language impairment; RT = reaction time; MO-SLI = monolingual specific language impairment; BI-SLI = bilingual specific language impairment.



The finding that monolinguals and bilinguals exhibited similar procedural learning effects and that children with SLI did not exhibit procedural learning is consistent with the notion that procedural learning is more biologically constrained and less malleable to environmental differences. Thus, individual differences in procedural learning perhaps reflect factors intrinsic to the learner (e.g., core learning abilities) rather than external environmental factors. Support for this interpretation comes from recent empirical findings (Finn et al., 2016; Leonard, Mackey, Finn, & Gabrieli, 2015). Leonard et al. (2015) found that although adolescents with lower SES exhibited poorer working memory performance than adolescents with higher SES, the two groups showed similar performance for procedural learning. Likewise, adolescents with lower SES showed smaller volumes of the neural substrates (hippocampus and dorsal lateral prefrontal cortex) that are associated with working memory than adolescents with higher SES, but the adolescents with lower and higher SES showed similar caudate volumes (a component of the basal ganglia) that are associated with procedural learning. Consistent with our interpretations, the authors concluded that procedural memory, unlike working memory, is less susceptible to environmental influences. Our study expands this finding to language experience and suggests that procedural memory is also less malleable to life experience in the form of language experience.

Although the finding that children with SLI did not exhibit significant effects of SRT learning is consistent with the procedural deficit hypothesis (Ullman & Pierpont, 2005) and with prior findings that reported difficulties in procedural learning in monolingual children with SLI (e.g., Lum et al., 2010, 2012; Tomblin et al., 2007), in the current study, we failed to replicate direct group differences between children with SLI and TD peers. This was the case for both monolinguals and bilinguals. Thus, although the children with SLI in our study appeared to have difficulty with procedural learning, those difficulties did not yield an obvious group difference, compared with TD peers. One possible explanation for this finding has to do with differences in sample sizes. Although our experiment was reasonably powered to examine our primary research question about differences in procedural learning among TD monolinguals and bilinguals (see power analysis in Method section), the sample size of children with SLI was relatively small. This may have resulted in a failure to detect either direct group differences between the SLI and TD groups or procedural learning effects in the SLI group. However, other studies have also failed to reveal direct group differences in SRT performance between children with SLI and TD (Gabriel, Stefaniak, Maillart, Schmitz, & Meulemans, 2012; Lum & Bleses, 2012; Lee & Tomblin, 2015). The lack of direct group differences in SRT performance is not consistent with the procedural deficit hypothesis, and at the moment, it is not fully clear what accounts for such results. Future research should examine under what conditions direct group differences between children with SLI and TD are found in SRT performance and under what conditions group differences are absent. This will be essential for verification of the procedural deficit hypothesis and any direct clinical implications based on it.

Another contrast between the current study and previous research is that, although we found no evidence of SRT learning in the SLI group, Tomblin et al. (2007) did find procedural learning by monolingual adolescents with SLI, albeit their learning rate was slower than their peers. The slower learning rate was revealed by growth curve modeling across the pattern phases. In the current study, smaller sample sizes ruled out the possibility of statistically examining growth curves within the SLI groups. However, in contrast to Tomblin et al.'s growth curve modeling, the comparison between early pattern and later pattern trials within the MO-SLI group indicated a lack of learning. Apart from differences in statistical approaches and sample size, the current study also differed from Tomblin et al.'s study in the age of the participants. In Tomblin et al.'s study, the participants were adolescents; in the current study, the participants were 8- to 12-year-olds. Therefore, it is possible that, in children with SLI, performance on the SRT task may improve between the ages of 8 and 15 years, in contrast to TD peers (Finn et al., 2016).

In sum, our data suggest that bilingual exposure does not shape procedural learning defined as acquiring sequential structure on the SRT task. Had we found defined advantages of bilingual exposure, one could have inferred that bilingual experience provides these children with an enhanced language learning mechanism, and the implication would have been that bilingualism may alleviate deficits in the affected learning mechanisms in SLI. Instead, we isolated aspects of procedural learning that bilingual experience does not shape in children with SLI or TD children. This suggests that the association between individual differences in this domain-general mechanism—the procedural memory system and individual differences in language learning—may be characterized by biological constraints rather than language experience.

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Appendix

Additional Statistical Analysis

Because the data were collected in Ontario and Pennsylvania for the typically developing (TD) groups, we determined whether we could combine the accuracy and reaction time (RT) data across the two different locations by comparing variances across locations and regression analyses with location as a predictor.

Accuracy. The Levene test was conducted to test whether there were equal variances in each group across the two different locations. The results confirmed that they all had equal variances, indicated by p-values greater than .05. Specifically, the monolingual-typically developing (MO-TD) group had equal variance of accuracy in Pattern 2, $F(1, 32) = 1.95$, $p = .172$, and in Random 2, $F(1, 32) = 2.33$, $p = .137$, and the bilingual-typically developing (BI-TD) group also had equal variance of accuracy in Pattern 2, $F(1, 22) = 0.00$, $p = .978$, and in Random 2, $F(1, 22) = 0.70$, $p = .413$, across the two different locations.

Next, we examined via regression analysis whether the location predicted the children's accuracy performance. The results revealed no significant effect of location, $\Delta F(1, 55) = .21$, $p = .647$, and no significant interaction between location and group (MO-TD or BI-TD), $\Delta F(1, 54) = 1.76$, $p = .191$, on accuracy in the second pattern phase. Similarly, neither the effect of location, $\Delta F(1, 55) = 1.78$, $p = .187$, nor the interaction between location and group (MO-TD or BI-TD), $\Delta F(1, 54) = .24$, $p = .630$, on accuracy in the second random phase were significant. Thus, we deemed it appropriate to combine the data across the location for the primary analysis.

Reaction time. The Levene test indicated that the MO-TD group had equal variance of the RTs in Pattern 2, $F(1, 32) = 0.50$, $p = .484$, and in Random 2, $F(1, 32) = 0.13$, $p = .723$, and the BI-TD group also had equal variance of the RTs in Pattern 2, $F(1, 22) = 0.90$, $p = .352$, and in Random 2, $F(1, 22) = 2.08$, $p = .163$, across the two different locations.

Second, we examined, via regression analysis, whether the location predicted the children's RT performance. The results revealed no significant effect of location, $\Delta F(1, 55) = 1.94$, $p = .169$, and no significant interaction between location and group (MO-TD or BI-TD), $\Delta F(1, 54) = 0.79$, $p = .379$, on RT in the second pattern phase. Similarly, neither the effect of location, $\Delta F(1, 55) = 0.12$, $p = .736$, nor the interaction between location and group (MO-TD or BI-TD), $\Delta F(1, 54) = 0.02$, $p = .896$, were significant predictors of RT in the second random phase. Thus, we deemed it appropriate to combine the data across the locations for the primary analysis.